Overview of Battelle Memorial Institute

For more information contact:
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216-898-6406
pestakc@battelle.org

Battelle's purposes stem from the will of steel industrialist Gordon Battelle

- Charitable trust
- Scientific research and development
- Creative activities of a scientific nature
- Reduction to practice and licensing of inventions, discoveries, and developments
- Advancement of learning and better education of men and women for employment (refueling the education pipeline)

Key Battelle Features

- Non-profit charitable trust — began operations in 1929
- 79 years of research and development leadership
- Major businesses are contract R&D, laboratory operations, and commercialization/commercial ventures
- Conduct more than $4 billion in annual R&D
  - More than 3,200 projects for 1,100 industrial and government customers
  - More than 130 locations
  - Conduct R&D business in more than 30 countries
  - 20,000 employees worldwide (including labs we manage or co-manage)

Major Technology Centers

Battelle
The Business of Innovation

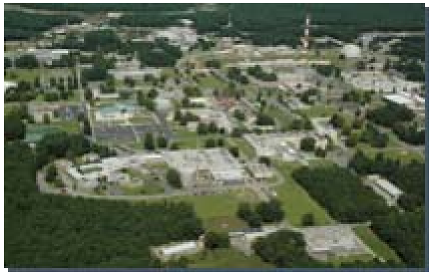
Battelle Corporate Headquarters
Columbus, Ohio

Ocean Sciences Laboratory
Duxbury, Massachusetts

Marine Sciences Laboratory
Sequim, Washington

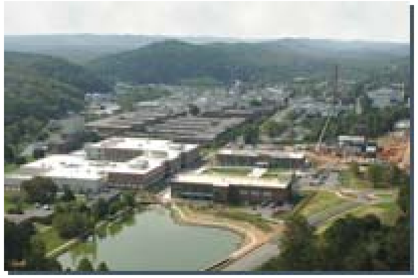
Battelle Europe
Geneva, Switzerland

Battelle Eastern Science and Technology Center
Aberdeen, Maryland



Brookhaven National Laboratory
Upton, New York

Pacific Northwest National Laboratory
Richland, Washington



Oak Ridge National Laboratory
Oak Ridge, Tennessee

National Renewable Energy Laboratory
Golden, Colorado

Idaho National Laboratory
Idaho Falls, Idaho

Lawrence Livermore National Laboratory
Livermore, California

National Biodefense Analysis and Countermeasures Center
Ft. Detrick, Maryland

Synergistic Businesses Operations

Laboratory Operations serves a national interest and provides the primary **source of S&T and IP** for clients of Global Business Units and Battelle Ventures

Global Business Units **integrates the S&T and IP** into innovative solutions to significant problems of clients for a fee, generating cash flow to support renewal and charitable distributions

Battelle Ventures provides contemporary **commercial marketplace knowledge** and significant financial returns to the Labs and Battelle, for renewal and distribution to the community

Assuring Sustainability of Battelle

Battelle Business Operations

Battelle
The Business of Innovation

Battelle

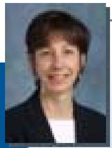
Carl F. Kohrt
President and CEO

Global Laboratory Operations

Jeffrey Wadsworth
Executive Vice President

Energy Science & Technology Global Business

Donald P. McConnell
Senior Vice President



Health & Life Science Global Business

Barbara L. Kunz
Senior Vice President

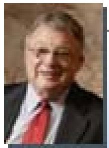
National Security Global Business

Stephen E. Kelly
Senior Vice President

GLOBAL BUSINESSES

International Partnerships

Richard C. Adams
Senior Vice President



Battelle Ventures

Mort Collins
General Partner

Contract R&D Clients

Battelle
The Business of Innovation

Some of Battelle's contract R&D clients:

Commercial

Johnson & Johnson	Mitsubishi
Ford	DuPont
Procter and Gamble	American Electric Power
Eli Lilly	Kodak
Emerson Electric	Invacare
Caterpillar	Honda
Bayer	Merck

Government

DOE	NASA
DoD	DOT
Homeland Security	NIH
EPA	HHS

Regional and Local Transportation Authorities

SOLAR THERMOCHEMICAL FUEL PRODUCTION

GREEN FORUM

GLENN RESEARCH CENTER

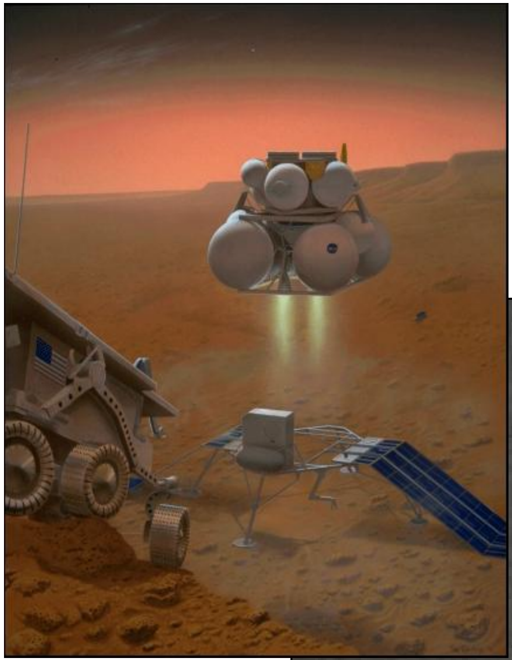
December 2, 2008

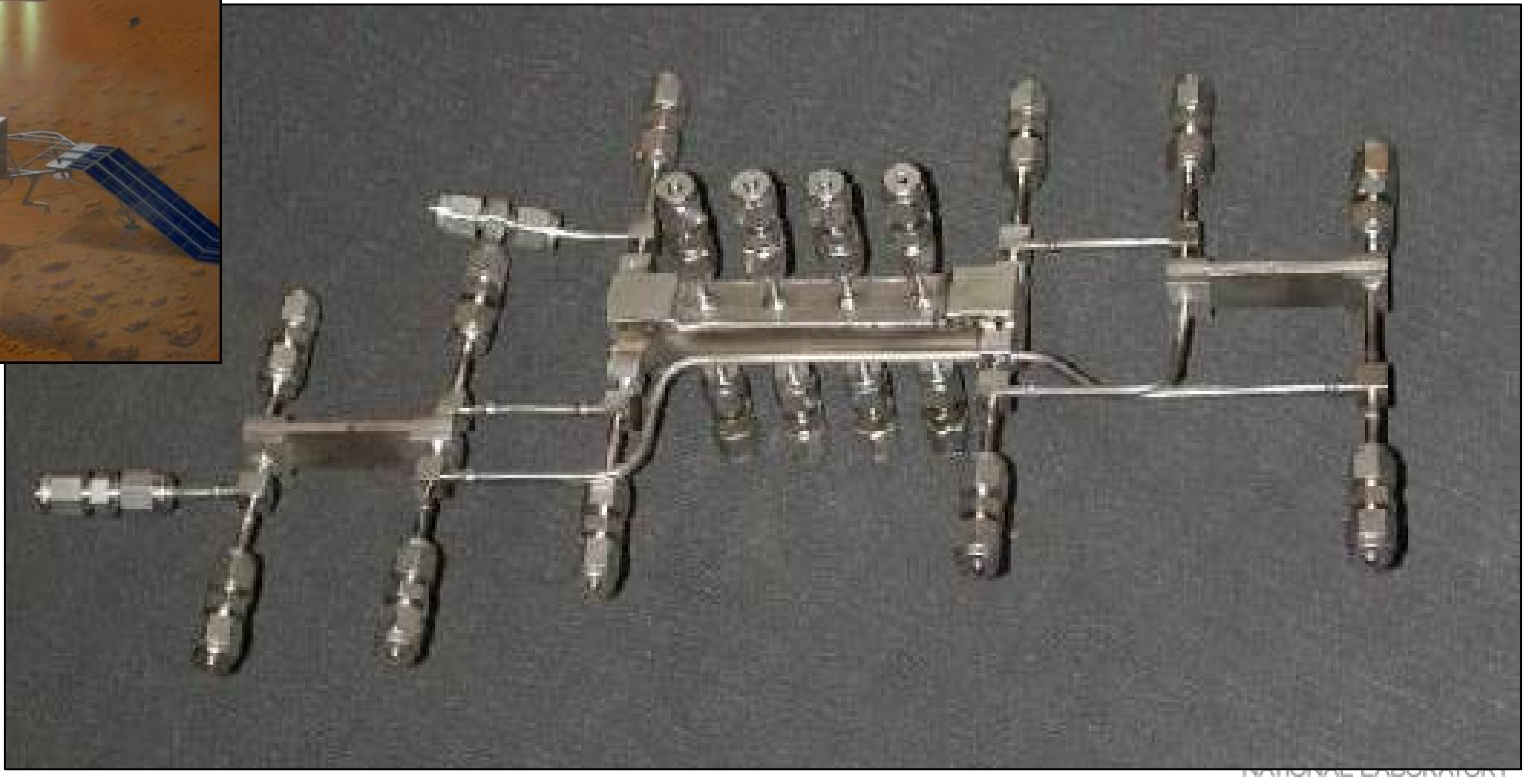
Robert S. Wegeng

Pacific Northwest National Laboratory,

Operated by Battelle Memorial Institute

Mars Sample Return Mission





Concentrating Solar Power (CSP) Methane Reforming Demonstration DLR / Sandia Demonstration, early 1990s

Energy Balance

Energy Choices Considered

- Direct Solar Only
- Direct Solar + Supplemental Energy

Feedstocks Considered

- Natural Gas (CH_4)
- Biomass (CH_4 + CO_2)
- Zero-Energy Chemicals (H_2O + CO_2)

SSP-Thermochemical Plant

Solar Fuels Considered

- Hydrogen (H_2)
- Synthetic Fuels (C_2H_{2n+2})
- Alcohols ($C_nH_{2n+1}OH$)

Waste Heat Out

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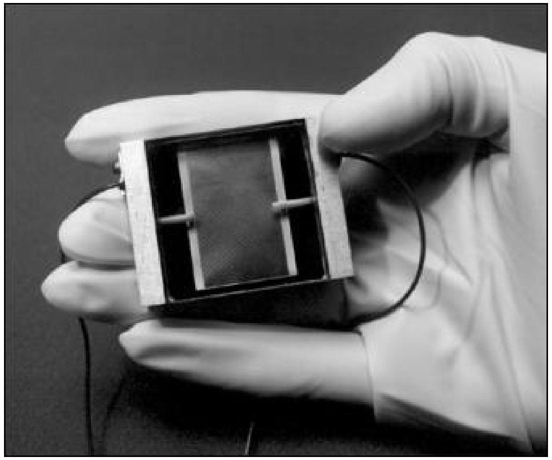
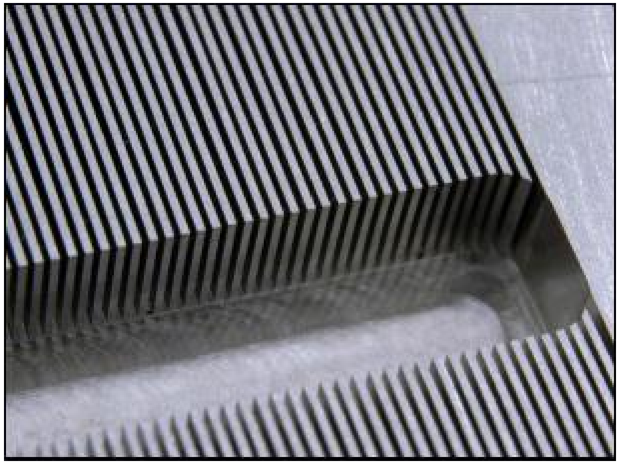
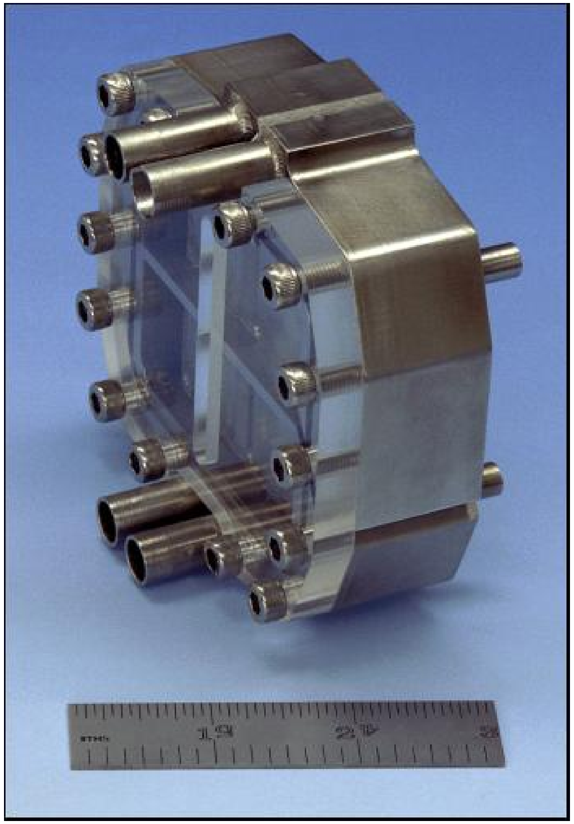
Additional Considerations

- Microchannel Process Technology







- Space Solar Power

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Outline

- Introduction
- Motivations
- Conventional: Solar Thermochemical
  - Operational Strategy
  - Concentrating Solar Thermal Power Systems
  - Solar Thermochemical Processing
  - Microchannel Process Technology
  - Production Estimates
- Non-conventional: Adding in Space Solar Power
  - Operational Strategy
  - Revised Production Estimates
- Conclusions

SOLAR THERMOCHEMICAL FUELS PRODUCTION

MOTIVATIONS

Motivations:
Energy Problems

- CO_2 Emissions // Global Warming
  - The debate has transitioned from whether the Earth is warming to a) how much? and b) what can we do about it?
- Peak Oil // Natural Gas // Coal
- Nuclear Energy // Nuclear Proliferation
- Oil Imports // Economics Impacts // Trade Deficits
  - The USA imports ~ 10 million barrels per day
  - = 3,650,000,000 barrels per year
  - @ ~$40 - $80 per barrel = $1.5 T - $3.0 T per decade
  - Economic impact [1] = $10 T - $20 T per decade

- ***An Apollo-magnitude program is warranted***

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Motivations:
Attributes of the "Holy Grail" Solution

1. Must solve the oil import problem
   - *It must produce transportation fuels*
2. Must efficiently utilize renewable solar energy
   - *It will be capital- and technology-intensive*
3. Must reduce Greenhouse Gas emissions
   - *It must enable a transition from carbonaceous feedstocks to carbon-neutral and/or carbon-negative feedstocks*
4. Must be financially attractive
   - *It must be profitable*
   - *It must attract funds from the world-wide capital investment market*

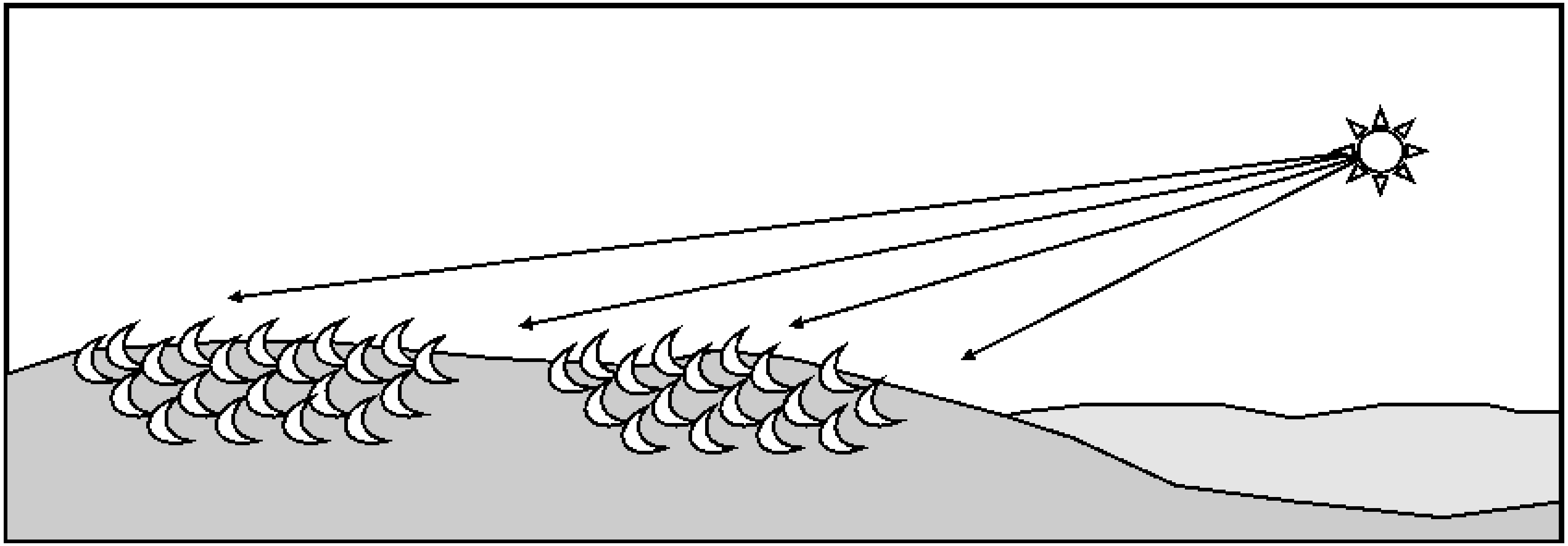
Solar Fuels

- Electrochemical
  - Typically ~25% efficiency in converting solar energy to electric energy in photovoltaic systems
  - Typically ~50-60% efficiency in converting electrical energy to chemical energy in electrolysis units
  - Overall efficiency: ~10-15%
- Photochemical (including photosynthesis)
  - Quantum efficiencies are typically very low
- ***Thermochemical***
  - ***Solar-to-thermal-to-chemical energy conversion efficiencies greater than 40% are demonstrated***
  - ***60% or higher is feasible for the solar chemical receiver***
  - ***Very high productivities are possible if feedstocks bring chemical energy***

SOLAR THERMOCHEMICAL FUELS PRODUCTION

CONVENTIONAL SOLAR THERMOCHEMICAL

Operational Strategy



Concentrating Solar Power (CSP)

Concentrating Solar Power (CSP)
10 MWe Power Generation

Concentrating Solar Power (CSP)
Infinia Corporation – 3 kWe units

Concentrating Solar Power (CSP)
Stirling Energy Systems (SES) – 25 kWe Unit

Concentrating Solar Power (CSP)
SES – 10,000 Parabolic Dish Concentrators

Concentrating Solar Power (CSP) Methane Reforming Demonstration DLR / Sandia Demonstration, early 1990s

Energy Balance

Energy Choices Considered

- Direct Solar Only
- Direct Solar + Supplemental Energy

Feedstocks Considered

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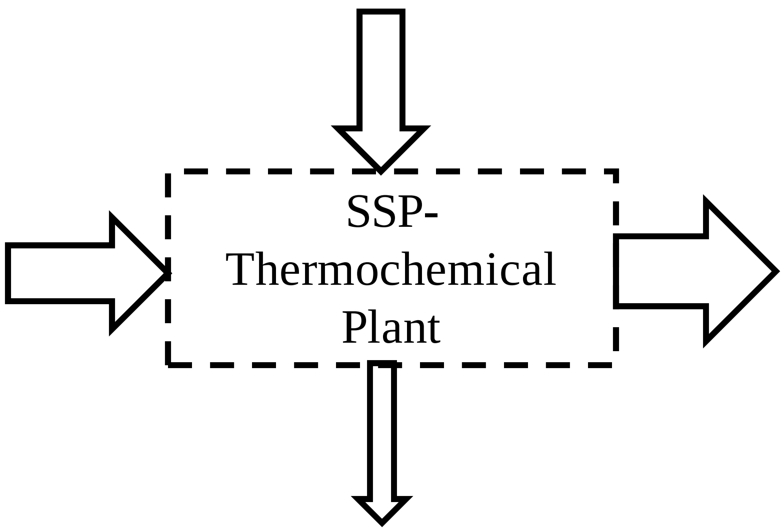
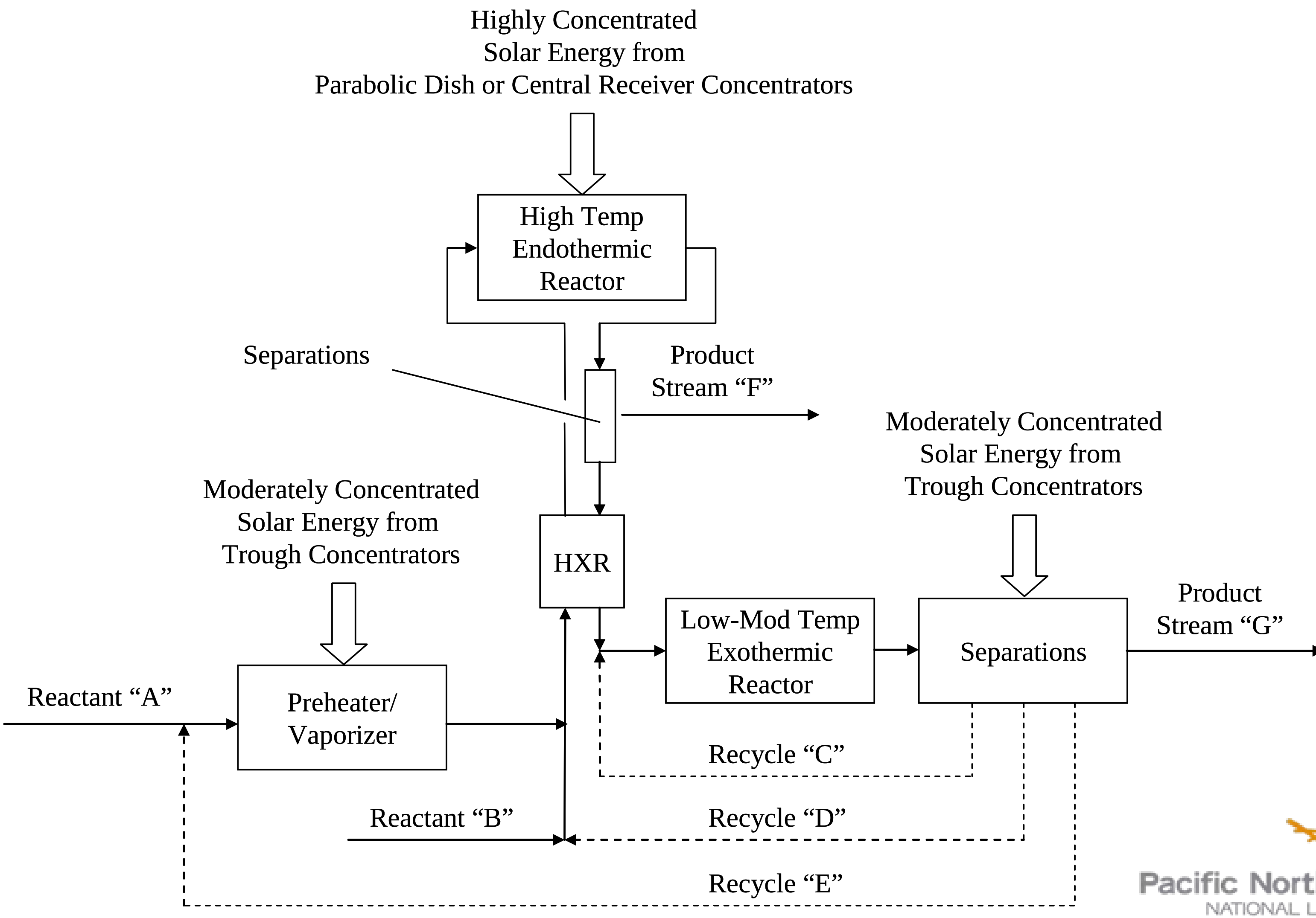


Solar Fuels Considered

- Hydrogen (H_2)
- Synthetic Fuels (C_2H_{2n+2})
- Alcohols ($C_nH_{2n+1}OH$)

Waste Heat Out

Generic Chemical Process Flowsheet



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Idealized Net Thermochemical Processes Evaluated

Table 1 - List of Chemical Reactions			
Reactants	**Primary Reactions**	**Net Thermochemical Process (Idealized)**	**Solar Fuels**
$CH_4 + H_2O$	Methane Reforming plus Water-Gas-Shift	$CH_4 + 2H_2O = 4H_2 + CO_2$	H_2
$CH_4 + H_2O$	Methane Reforming plus Fischer-Tropsch	$nCH_4 = C_nH_{2n+2} + (n-1)H_2$	$C_nH_{2n+2} + H_2$
$CH_4 + CO_2$	Methane Reforming plus Fischer-Tropsch	$(3n+1)/4\ CH_4 + (n-1)/4\ CO_2 = C_nH_{2n+2} + (n-1)/2\ H_2O$	C_nH_{2n+2}
H_2O	Water-Splitting Processes	$H_2O = H_2 + ½O_2$	H_2
$CO_2 + H_20$	Water-Splitting Processes plus Reverse Water-Gas Shift and Fischer-Tropsch	$nCO_2 + (n+1)H_2O = C_nH_{2n+2} + (3n+1)O_2$	C_nH_{2n+2}

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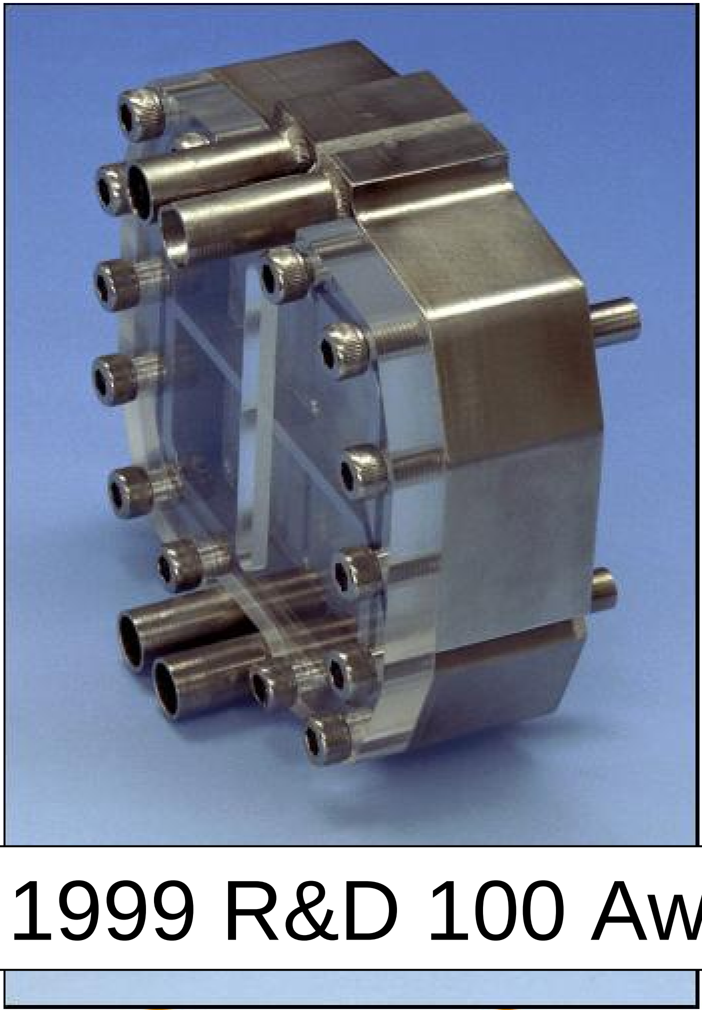
MICROCHANNEL PROCESS TECHNOLOGY
compact chemical processing chip



- Four cells each of microchannel reactors and heat exchangers
- Volume: 0.3 liters
- Processes/combusts 1400 SLPM

1999 R&D 100 Award Winner

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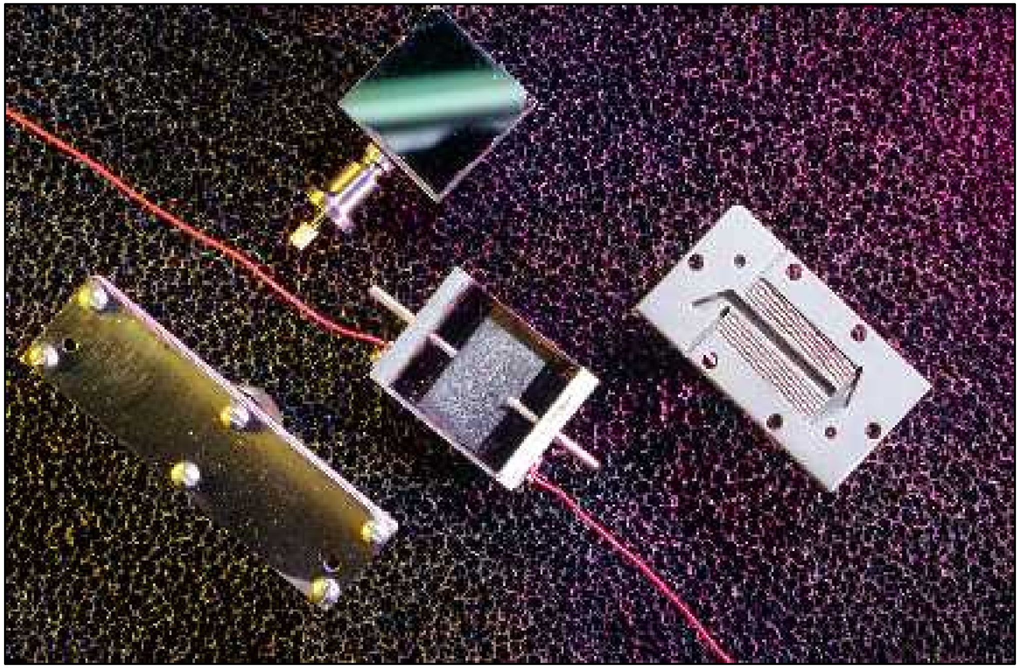
New Tools: Microchannel Process Technology

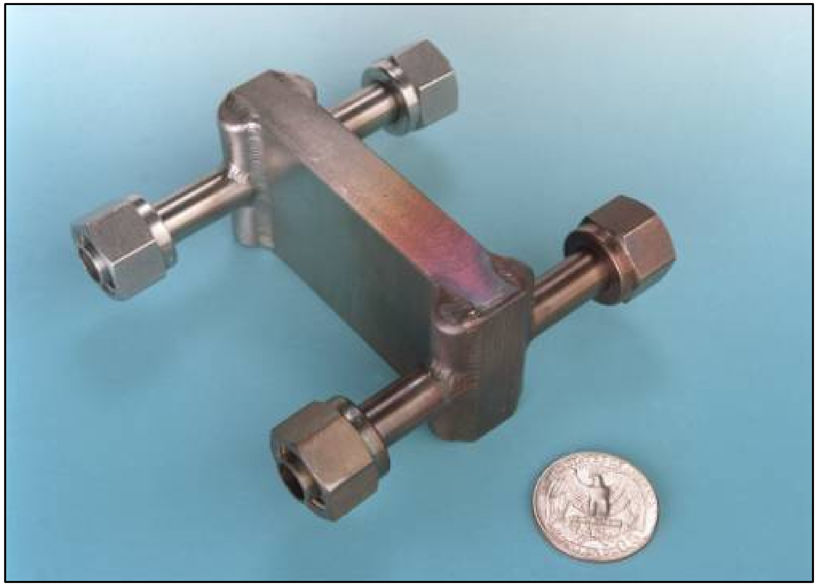
- Microchannel Heat Exchangers, Reactors and Separations units
- Miniaturization:
  - Process Intensification
  - High capacities
  - Lightweight systems
  - Mass Production

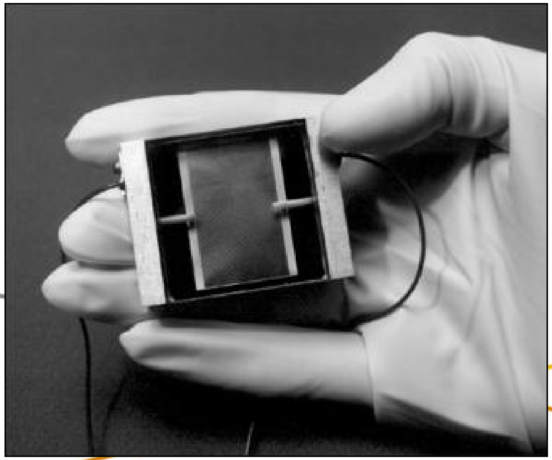


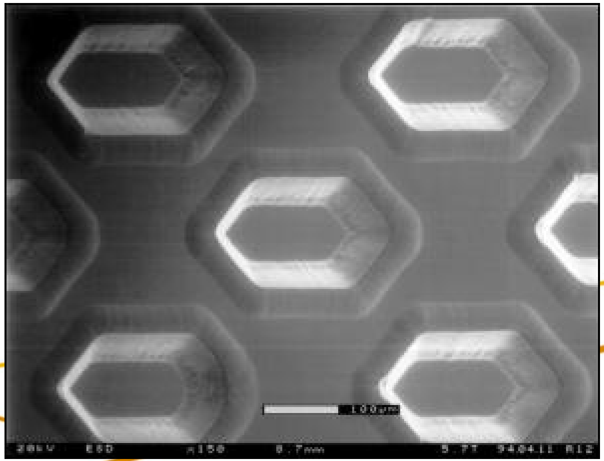
DARPA/DOD:	MEMS, Mesoscopic Machines
NASA:	Micro/Nano Systems
Department of Energy	MicroCATS
AICHE/DECHEMA	Microreaction Technology

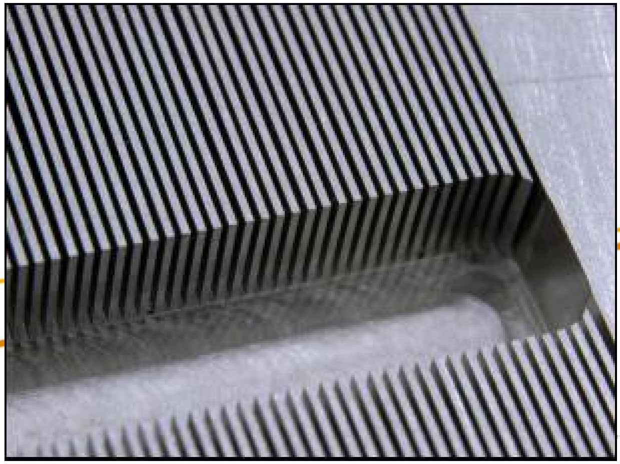
Microchannel Heat Exchangers

- **High heat duties**
  - **10 – 100 watts/cm^3**
- **Low pressure drops**
- **High heat transfer effectiveness**
  - **Up to 90% (or greater)**



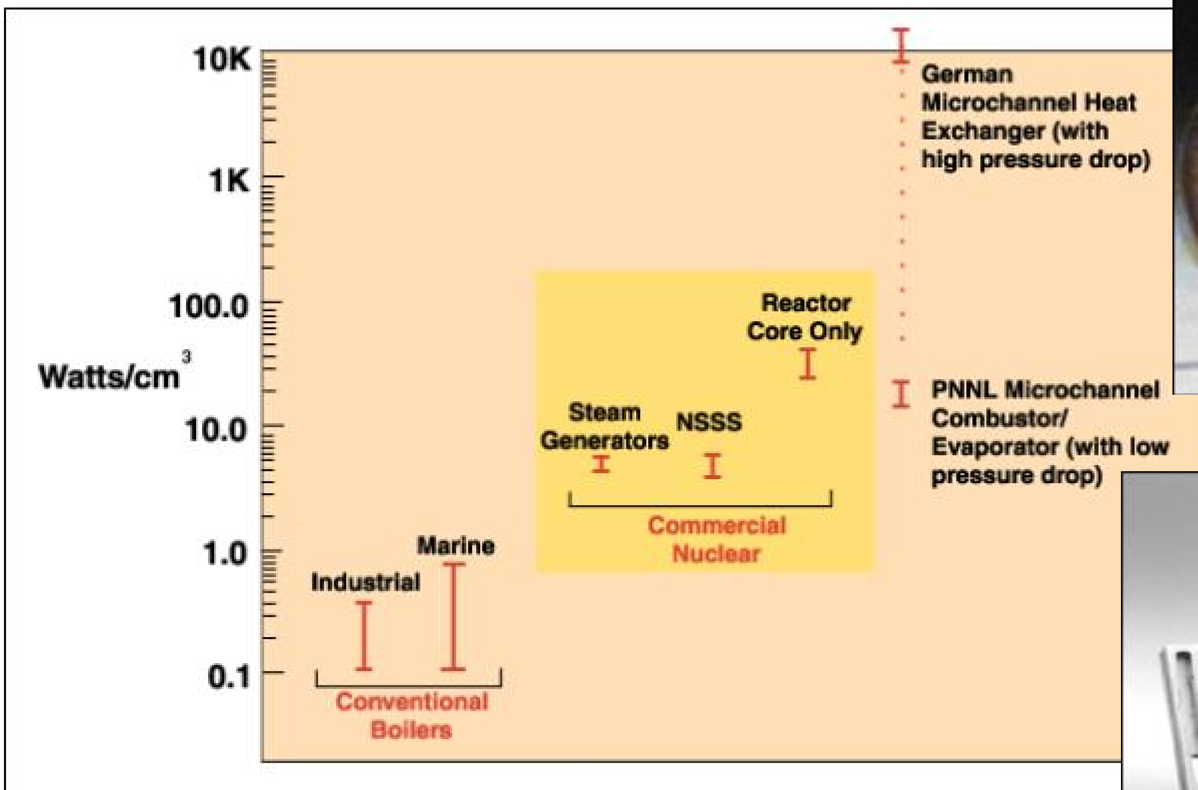


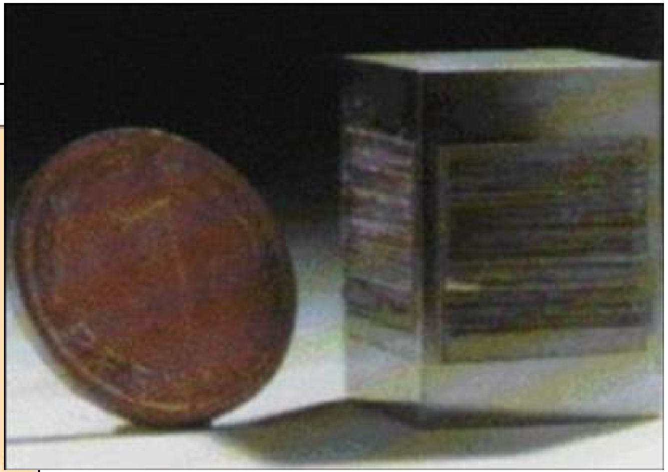


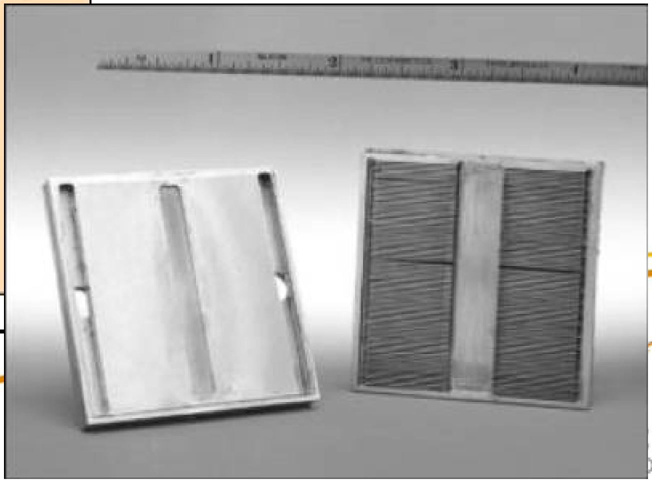


MICROCHANNEL HEAT EXCHANGER DUTY

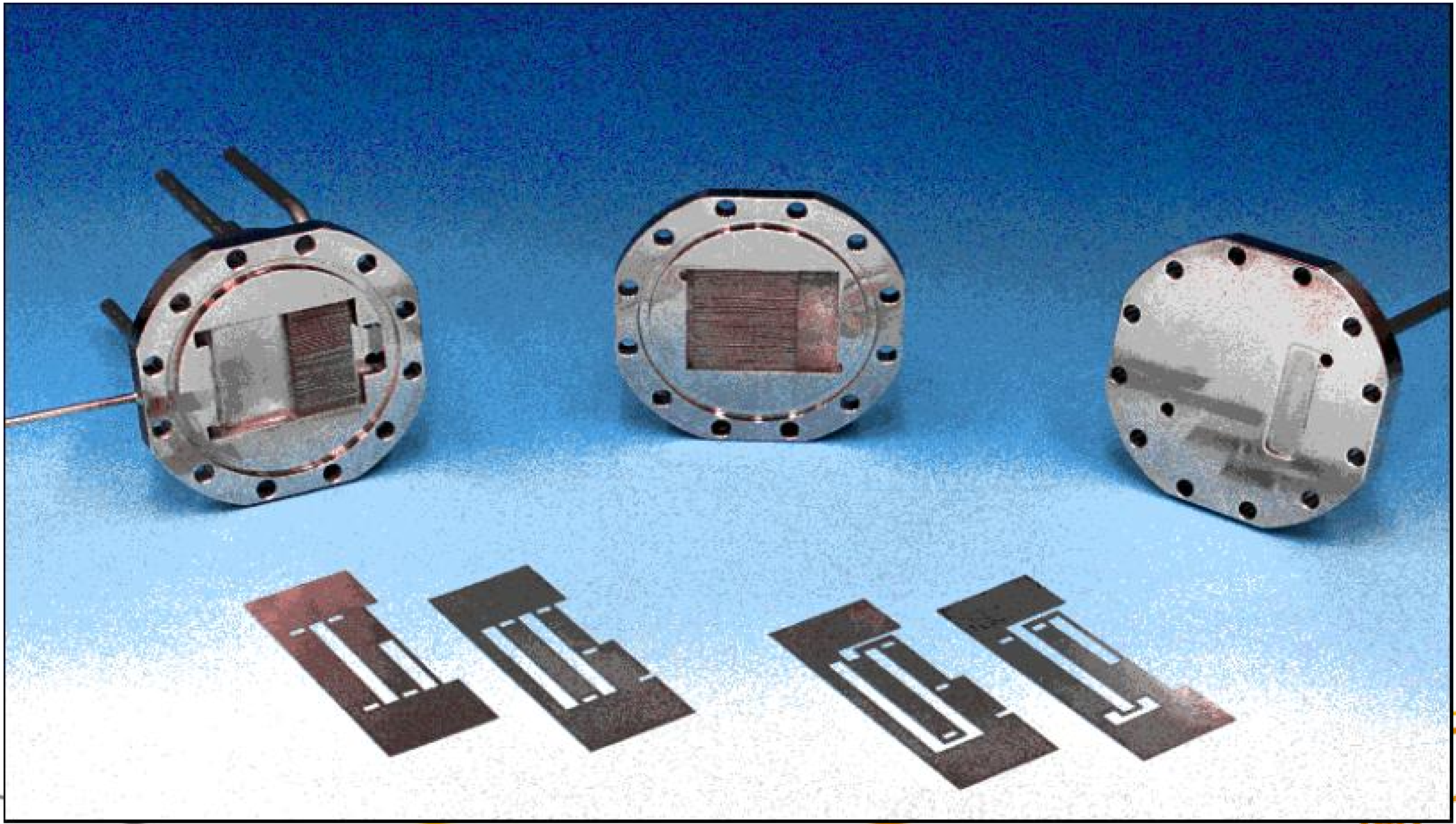
Heat transfer per unit hardware volume



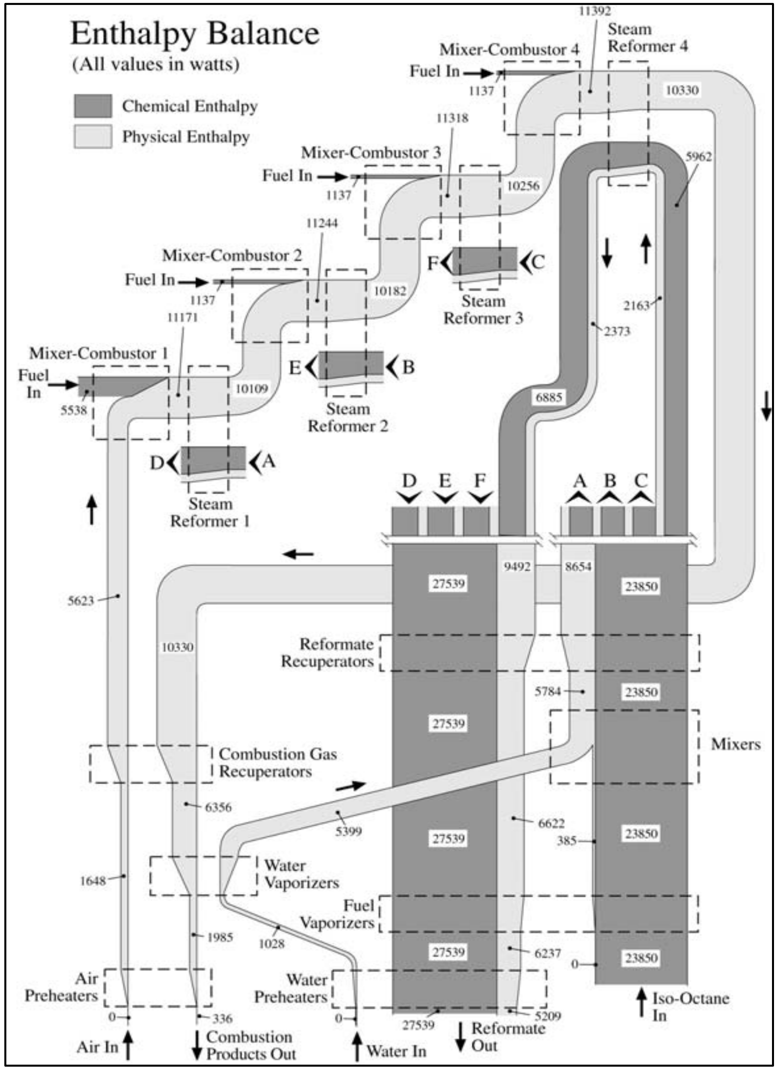




FABRICATION FOR MASS PRODUCTION

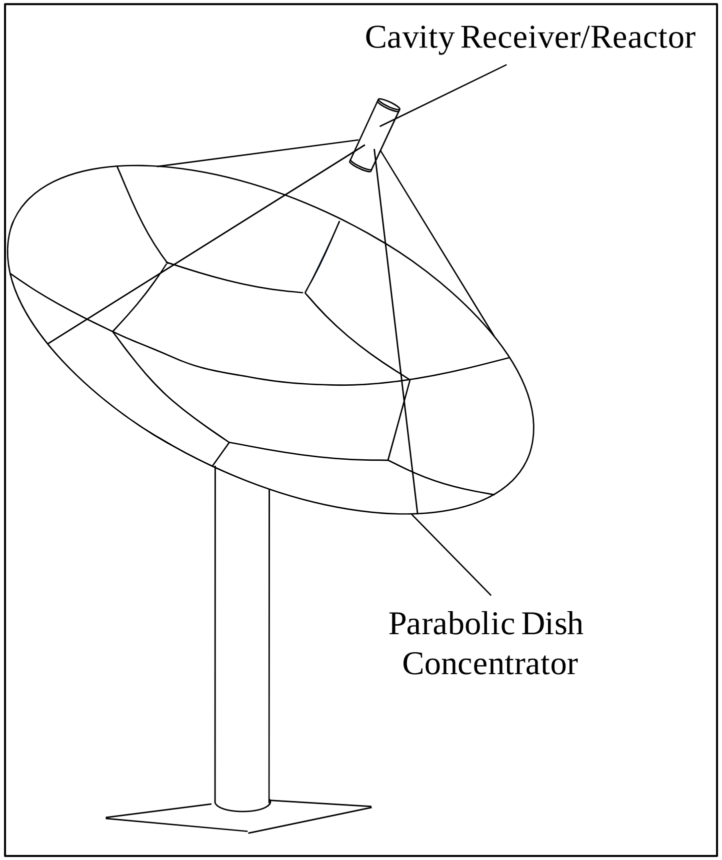


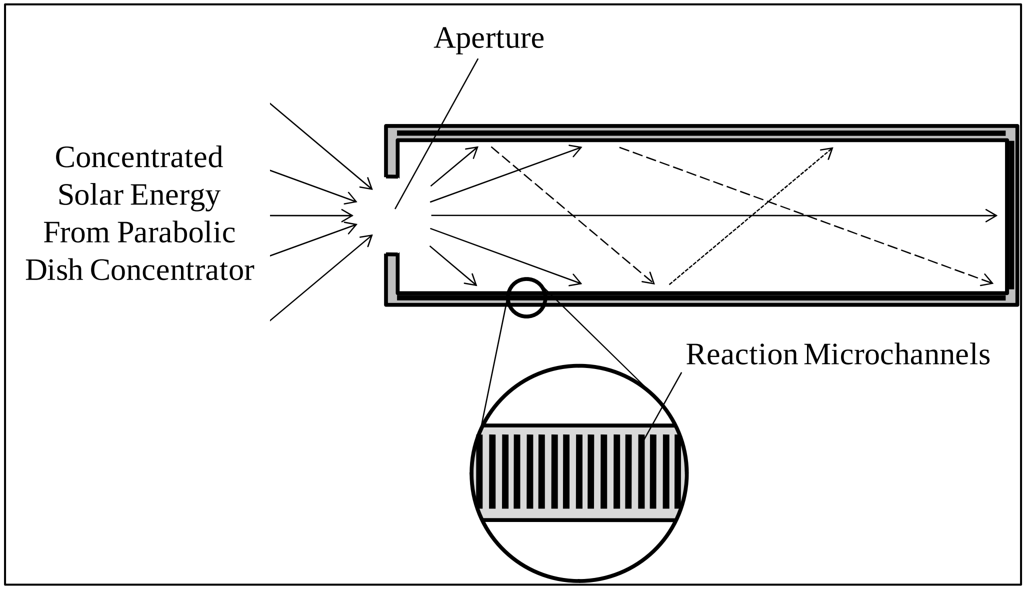
Efficient, Process-Intensive Microchannel Process Technology



“Chemical Process Chips”

Microchannel Cavity Reactor/Receiver





Production Estimates
10,000 Dish System

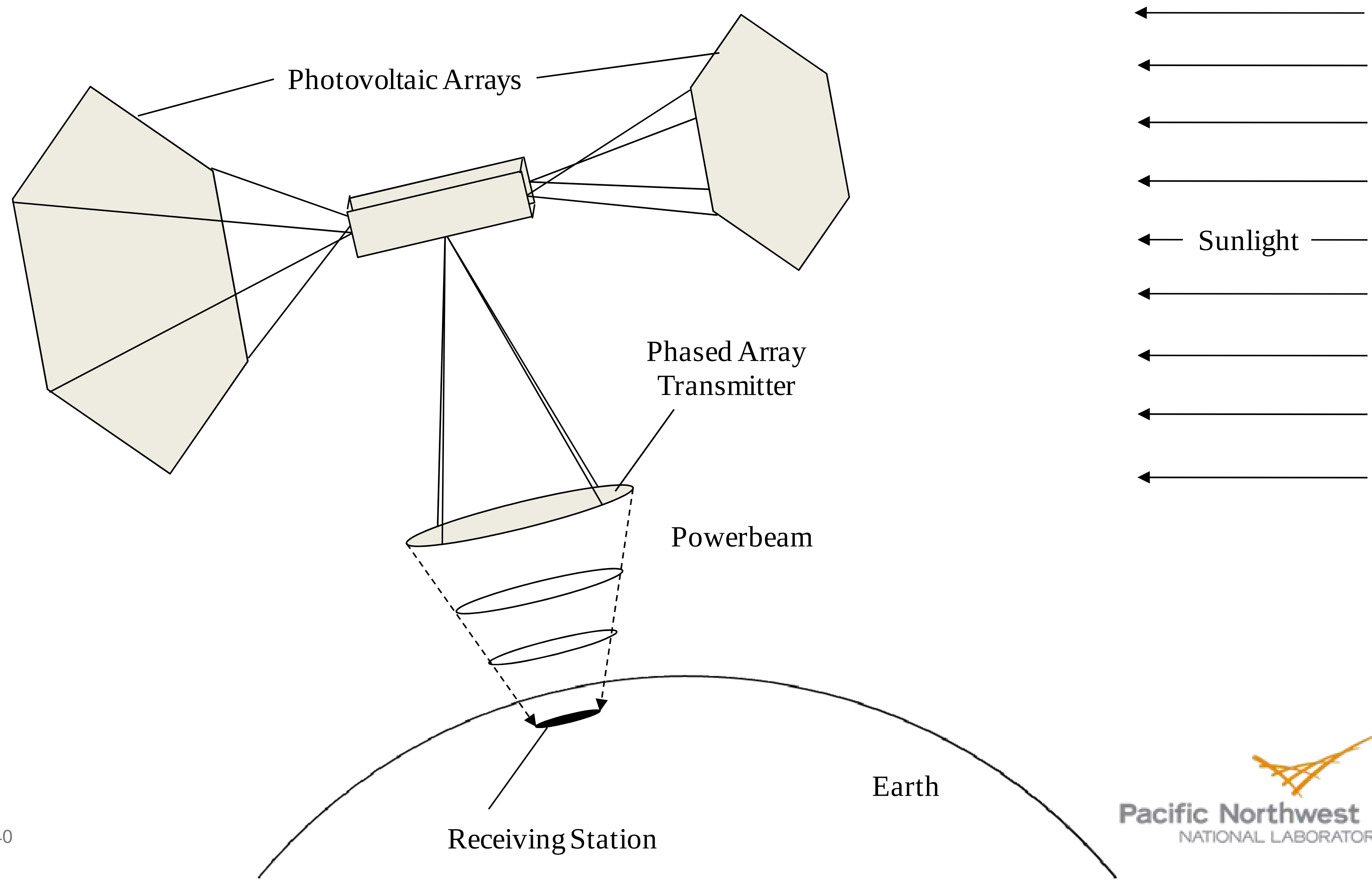
- 100 kWs per dish
- 1 GWs total
- Occupies a few square kilometers

SOLAR THERMOCHEMICAL FUELS PRODUCTION

NON-CONVENTIONAL:

ADDING IN SPACE SOLAR POWER

SSP – Baseline Concept



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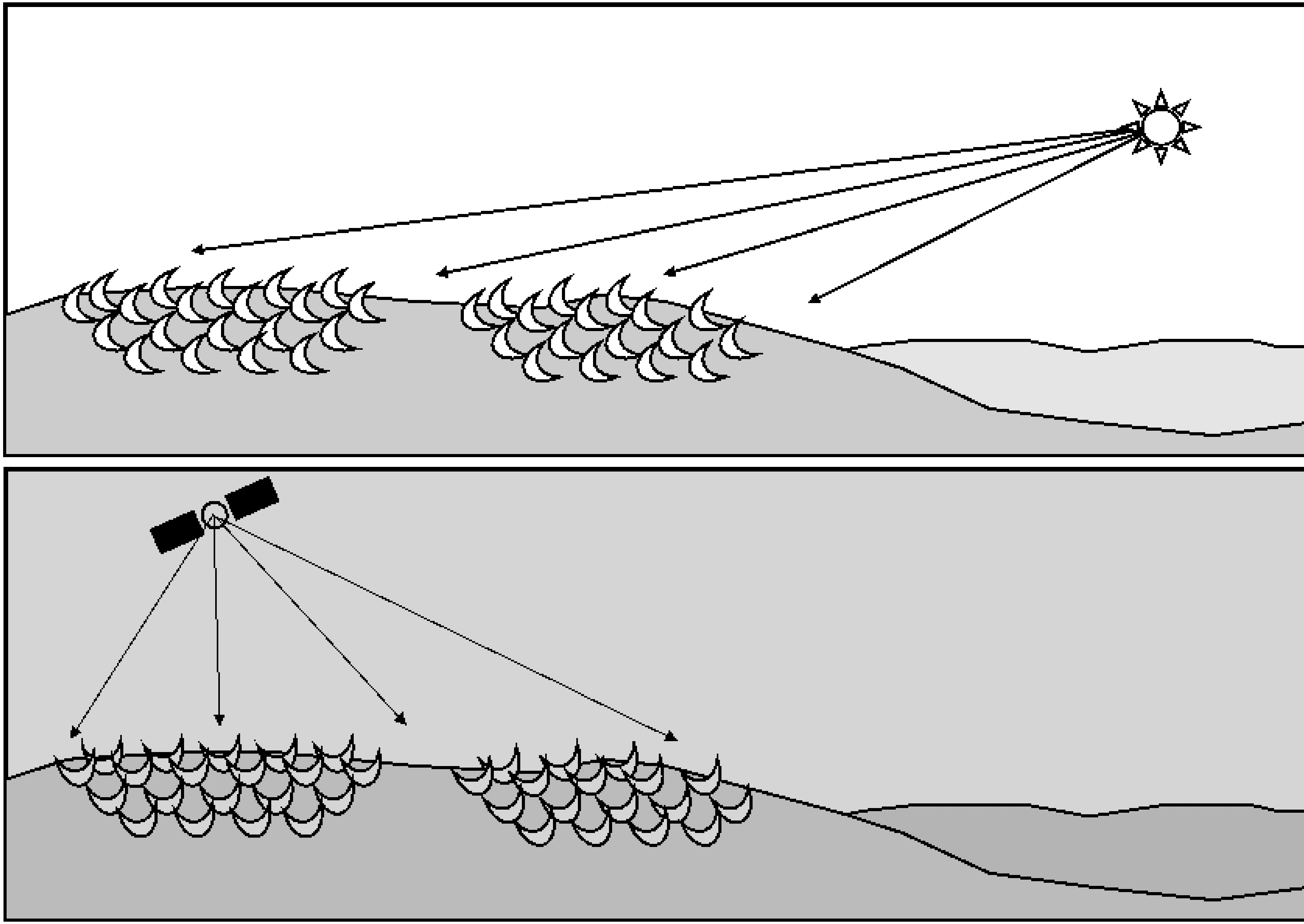
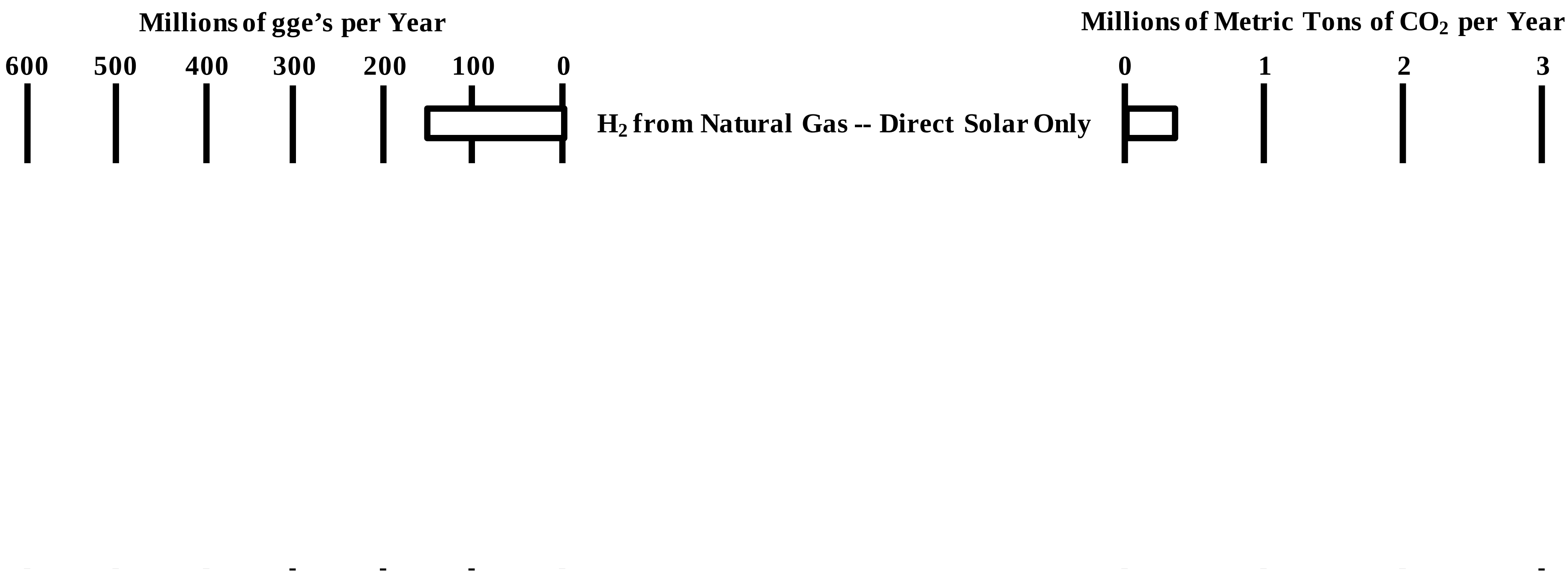
Operational Strategy Including Space Solar Power



Production Estimates using SSP Energy 10,000 Dish System



- Space Solar Power supports additional reductions in fossil fuel consumption and CO_2 emissions

SOLAR THERMOCHEMICAL FUELS PRODUCTION

CONCLUSIONS

Conclusions - I

- A "reference Solar-Thermochemical Plant"
  - 10,000 dishes *over a few square kilometers*
  - Collectively intercepting 1.0 GW_r
  - Thermochemical efficiencies in the Receiver of 40% *or greater* are possible
  - Can produce ~10^6 gge/day (if biomass is the feedstock)
  - Reducing CO_2 emissions by over 2,000,000 MT/year
- Forty "reference plants" using biomass as the feedstock
  - Would require 100 – 200 square kilometers
  - Could offset ~10% of USA oil imports
  - Reducing transportation sector CO_2 emissions by ~6.6%

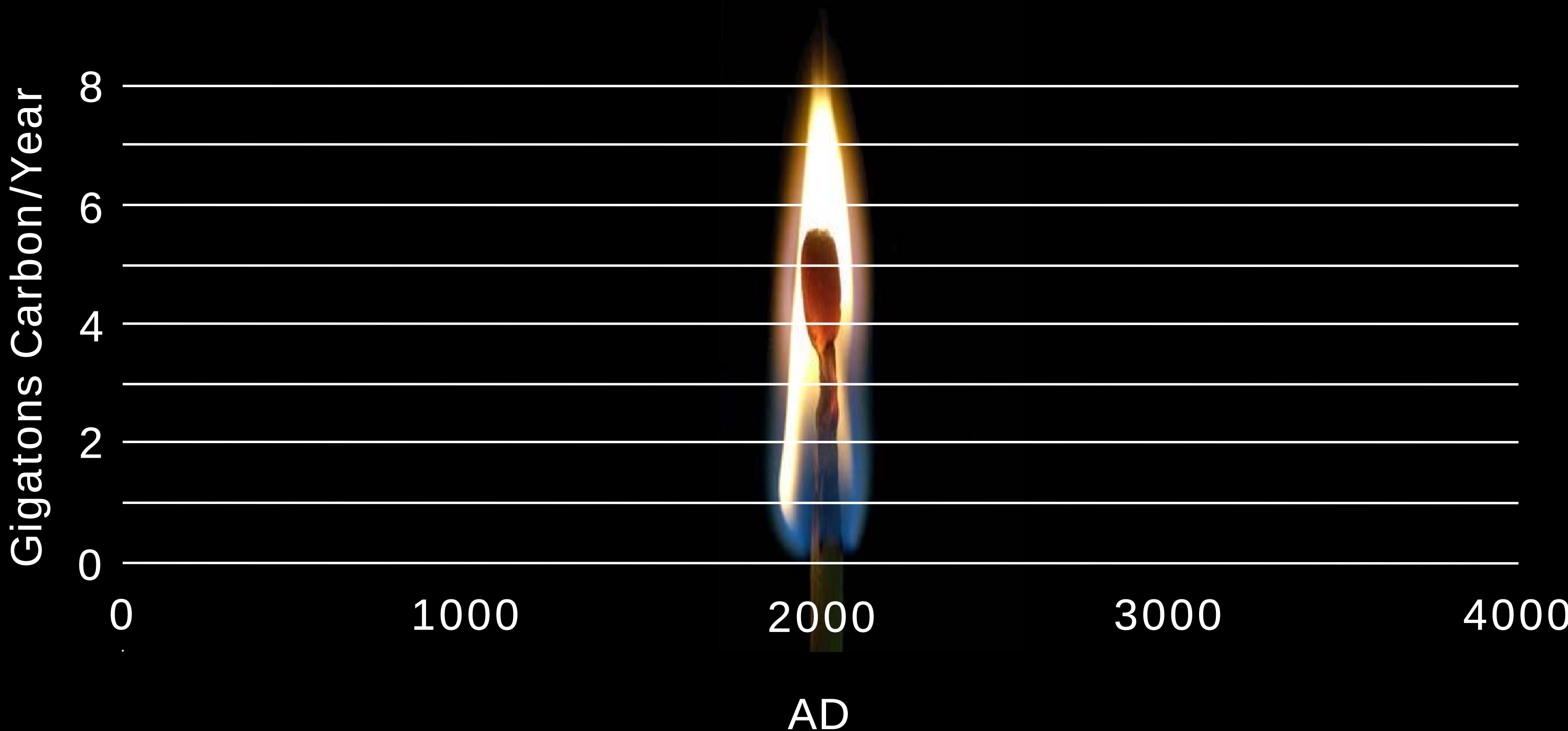
Conclusions - II

- System concept does not depend on Space Solar Power
- Hybrid plants, using sunlight AND the powerbeam from an orbiting satellite, can
  - Increase the production of solar fuels
  - And reduce fossil fuel consumption and net CO_2 emissions
- However, Space Solar Power is still an “iffy” proposition

Conclusions - III

- Economic benefits of successfully developing solar fuels:
  - $10 T – $20 T per decade (national)
  - Reductions in CO_2 emissions

FOSSIL ENERGY
“a single match”



SOLAR ENERGY